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Antarctic sea ice thickness and snow-to-ice conversion from atmospheric reanalysis and passive microwave snow depth

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[1] Passive microwave snow depth, ice concentration, and ice motion estimates are combined with snowfall from the European Centre for Medium-Range Weather Forecasting (ECMWF) reanalysis (ERA-40) from 1979–2001 to estimate the prevalence of snow-to-ice conversion (snow-ice formation) on level sea ice in the Antarctic for April–October. Snow ice is ubiquitous in all regions throughout the growth season. Calculated snow-ice thicknesses fall within the range of estimates from ice core analysis for most regions. However, uncertainties in both this analysis and in situ data limit the usefulness of snow depth and snow-ice production to evaluate the accuracy of ERA-40 snowfall. The East Antarctic is an exception, where calculated snow-ice production exceeds observed ice thickness over wide areas, suggesting that ERA-40 precipitation is too high there. Snow-ice thickness variability is strongly controlled not just by snow accumulation rates, but also by ice divergence. Surprisingly, snow-ice production is largely independent of snow depth, indicating that the latter may be a poor indicator of total snow accumulation. Using the presence of snow-ice formation as a proxy indicator for near-zero freeboard, we examine the possibility of estimating level ice thickness from satellite snow depths. A best estimate for the mean level ice thickness in September is 53 cm, comparing well with 51 cm from ship-based observations. The error is estimated to be 10–20 cm, which is similar to the observed interannual and regional variability. Nevertheless, this is comparable to expected errors for ice thickness determined by satellite altimeters. Improvement in satellite snow depth retrievals would benefit both of these methods.

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1. Introduction

[2] Precipitation is expected to increase substantially over the polar regions with increased greenhouse warming [*Emori and Brown*, 2005]. In the Antarctic, this has important implications for ice sheet mass balance and sea level rise. Part of this expected increase is due to a concomitant reduction in sea ice coverage [e.g., *Krinner et al.*, 2007; *Bromwich et al.*, 1998]. While there has been much interest in accumulation over the Antarctic continent [e.g., *Bromwich*, 1988; *Vaughan et al.*, 1999; *Arthern et al.*, 2006; *van de Berg et al.*, 2006], little effort has been undertaken to evaluate precipitation over sea ice in the Southern Ocean, in part due to the almost complete lack of observations. However, precipitation rates over the sea ice are much higher than over the continent. Accurate estimates of precipitation are vitally important for modeling sea ice thickness [e.g., *Fichefet and Morales Maqueda*, 1999; *Fichefet et al.*, 2000], the freshwater balance of the Southern Ocean [*Häkkinen*, 1995], and influence of snow-covered sea ice on global climate [*Ledley*, 1991].

[3] One of the most important consequences of high snowfall rates on Antarctic sea ice is snow-to-ice conversion through the formation of snow ice. Snow ice is granular-textured sea ice that has frozen from a mixture of meteoric ice (snow) and seawater or brine. Flooding of the ice surface occurs when the snow load is sufficient to depress the ice surface below sea level and seawater and brine infiltrate the base of the snow pack. When the resultant slush freezes, snow ice is formed. Under present day conditions, model results suggest that the impact of a snow cover is to increase ice thickness through snow-to-ice conversion rather than reduce thickness owing to insulation [*Fichefet and Morales Maqueda*, 1999; *Powell et al.*, 2005], although *Eicken et al.* [1995] suggest the opposite for the Weddell Sea. In contrast, excessive snowfall has been implicated as a possible contributing factor to the rapid decline of sea ice in the Bellingshausen Sea [*Jacobs and Comiso*, 1993]. *Jeffries et al.* [2001] suggest that roughly half the snow cover on sea ice in the Pacific sector of the Southern Ocean is converted into snow ice. Flooding and snow-ice formation are also

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important factors for remote sensing [*Drinkwater and Lytle*, 1997] and biological productivity [*Fritsen et al.*, 1998]. Where snow-ice formation is widespread, there is a strong relationship between mean snow depth and ice thickness [*Worby et al.*, 1996; *Jeffries et al.*, 1998b], raising the intriguing possibility that in these instances, ice thickness can be estimated from snow depth. Quantifying the prevalence of snow ice is therefore important in evaluating its role in climate processes as well as evaluating estimates of snowfall over sea ice.

[4] Snow ice has been observed in all regions and seasons in Antarctic pack ice [*Lange et al.*, 1990; *Allison and Worby*, 1994; *Eicken et al.*, 1994; *Jeffries et al.*, 1994, 1997a, 1998b, 2001], forming a significant fraction of the total sea ice mass; estimates range from about 7% in the Weddell [*Lange et al.*, 1990] to 38% in the Amundsen and eastern Ross seas [*Jeffries et al.*, 1998b]). There is considerable uncertainty in estimates of snow-ice thickness, however. Snow ice is usually identified using stable isotope analysis, since the strongly negative δ^{18}O values of meteoric ice readily distinguish it from ice of seawater origin. However, brine exchange during freezing is thought to modify the isotopic composition of the bulk sea ice [*Lytle and Ackley*, 2001; *Maksym and Jeffries*, 2001]. Slightly different choices of δ^{18}O values to discriminate between ice types leads to a wide range of estimates for the contribution of snow ice to the total ice thickness [*Jeffries et al.*, 1997a; *Maksym*, 2001]. This results in a disparity between estimates of the contribution of meteoric ice (0.6–8%) and of snow ice (12–38%) to the total ice thickness in the Ross, Amundsen and Bellingshausen seas [*Jeffries et al.*, 2001] . Without better understanding of the role of phase-change and brine-exchange processes in controlling the isotopic composition during evolution of the ice, an assessment of the contribution of snow to the mass balance of Antarctic sea ice from ice core data alone remains problematic.

[5] Several large-scale sea ice models have attempted to address the issue of snow-ice mass balance [*Fichefet and Morales Maqueda*, 1999; *Fichefet et al.*, 2000; *Wu et al.*, 1999]. In all of these, snow-ice thicknesses similar to in situ observations were produced only at the expense of too deep a snow cover. *Fichefet and Morales Maqueda* [1999], the only study to report the spatial distribution of snow ice, produce a distribution inconsistent with in situ observations [*Jeffries et al.*, 2001; *Worby et al.*, 1998]. None of these models account for either the sub-grid-scale ice and snow thickness distribution, which could have consequences for the prevalence and distribution of flooding and snow-ice formation. No studies investigate the interannual variability of snow depth and snow-ice formation.

[6] Passive microwave estimates of snow depth on sea ice [*Markus and Cavalieri*, 1998] can, in principle, provide an independent data set with which to force snow-on-sea-ice models. However, care must be taken as the snow depth is also a prognostic variable controlled by snowfall, snow-to-ice conversion, and ice advection. *Powell et al.* [2005] addressed this problem through assimilation of satellite snow depths by optimal interpolation. They suggest that precipitation rates from reanalyses are too high by a factor of 2. This is difficult to reconcile with the general agreement with field observations over the continent [*Monaghan et al.*, 2006a], even capturing interdecadal variability.

[7] This study attempts to address four main questions: (1) What is the prevalence of snow ice in the Antarctic ice pack; namely, can model estimates be reconciled with in situ estimates of snow-ice thickness and observed snow depths, (2) can we infer the accuracy of snowfall estimates from atmospheric analyses using satellite-based snow depths and computed snow-ice thickness, (3) what controls the variability in snow-ice production, and perhaps most intriguingly, (4) can satellite-based snow depth and snowfall from reanalysis provide a possible proxy for thickness of level sea ice?

[8] To address these questions we use a simple model to estimate the contribution of snow ice to sea ice mass balance for the growth season (April–October) for the period 1979–2001. To do this we use four data sets: snowfall from the European Centre for Medium-Range Weather Forecasting (ECMWF) ERA-40 reanalysis and three satellite passive microwave data sets of snow depth, ice concentration, and ice motion. The ice concentration and ice motion products are used to estimate the production of new, snow-free ice, and hence predict the monthly change in snow depth in the absence of accumulation. The difference between this and the next month's satellite snow depth is then compared with the predicted accumulation from ERA-40 to estimate the rate of snow-to-ice conversion.

[9] In section 2 we discuss the data sets used, examine trends and interannual variability in snowfall and snow depth, and describe the methodology in more detail. Snow-ice thickness maps are derived, factors controlling variability are discussed and results are compared to in situ data in section 3. In section 4, we examine the possibility of estimating level-ice thickness from satellite snow depth. Results are compared with in situ observations from the Antarctic Sea ice Processes and Climate (ASPeCt) program of the Scientific Committee on Antarctic Research. Finally, we discuss the interpretation of the results and implications for comparison with other data sets.

2. Data and Methods

2.1. Data

[10] Sea ice concentrations from two algorithms are widely used to investigate long-term changes in the Arctic and Antarctic sea ice covers: the Bootstrap and the NASA Team algorithm. Advantages and limitations are discussed by *Comiso et al.* [1997]. The primary differences are that the Bootstrap algorithm underestimates sea ice concentration along the coast, especially in areas of thin ice, while the NASA Team algorithm underestimates ice concentrations in the outer pack. To study the snow depth on sea ice, errors over thin ice regions are less critical because the snow depth is generally close to zero. We therefore use Bootstrap ice concentrations that have been adjusted for temporal consistency in this study. The data are available at the National Snow and Ice Data Center [*Comiso*, 1999].

[11] Snow depth is derived from passive microwave brightness temperatures following *Markus and Cavalieri* [1998]. Originally developed using sea ice concentration from the NASA Team 2 algorithm [*Markus and Cavalieri*, 2000], it has been extended to cover both the SSM/I and SMMR periods using Bootstrap ice concentrations by tuning the algorithm to match the derived snow depths for

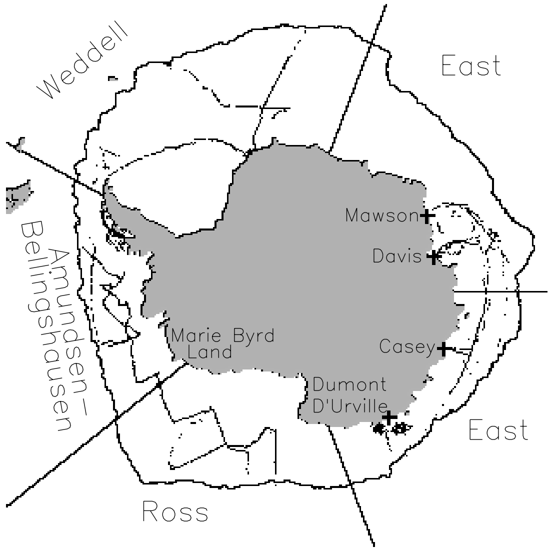

Figure 1. Location map of the four regional divisions used in this study. The mean September sea ice extent is shown, along with the locations of all ASPeCt snow and ice observations available from August to October. Several locations mentioned in the text are also indicated.

the period of overlap between the two data sets. Hereafter, we refer to this snow depth product as satellite snow depth. Due to the simplicity of the algorithm, significant errors are possible due to the effects of variable grain size, snow layering and wetness, and weather effects [*Markus and Cavalieri*, 1998; *Markus et al.*, 2006]. However, on regional scales, the correlation with snow depth distributions from ship-based measurements is quite good. The satellite snow depths underestimate the observed snow depths by an average of 3.5 cm [*Markus and Cavalieri*, 1998]. Because of the substantial effects of snow wetness and freeze/thaw cycles on snow depth retrievals, this study is limited to the cold winter months of April to October.

[12] Sea-ice motion is obtained from monthly-mean ice drift vectors derived from a combination of passive microwave, Advanced Very High Resolution Radiometer (AVHRR), and drifting buoys [*Fowler*, 2003]. While this is the best ice motion data set currently available, it has been shown to significantly underestimate ice drift in the East Antarctic sector of the Southern Ocean [*Heil et al.*, 2001b].

[13] Snowfall is taken from the ERA-40 reanalysis project [*Uppala et al.*, 2005]. The data are interpolated from an N80 reduced gaussian grid (spatial resolution approximately 1.125°) onto the SSM/I grid (pixel size of 25 km). The snowfall fields are produced from 6-hour forecasts. *Turner et al.* [1999] show that such short forecasts tend to underestimate precipitation by about 9% for ERA-15. This effect is presumably less important in ERA-40, and not critical here, given the simplicity of the model used. We use snowfall rather than the more traditional precipitation minus evaporation (P-E) [e.g., *Bromwich*, 1988] because evaporation over ice-covered seas is dominated by evaporation in leads and polynyas, while over sea ice in winter the net evaporation is likely small. A comparison of precipitation and snowfall in the ERA-40 data show that the fraction of liquid precipitation can be significant near the ice edge. This is supported by evidence for widespread rain-on-snow events that lead to thin icy crusts [*Sturm et al.*, 1998]. *Massom et al.* [1997], however, note that rain can remove much of the snow cover. It is presently unclear how liquid precipitation affects the mass balance of the snow, or how its effects might impact passive microwave retrievals of snow depth. We therefore consider only the snowfall. Snowfall is converted from snow water equivalent to snow depth using a density of 350 kg m^{-3}, which is a good estimate for the mean winter snow density [*Massom et al.*, 2001].

[14] The accuracy of the snowfall forcing is critical to our estimates of snow-ice thickness. On the continent, both ERA-15 [*Turner et al.*, 1999] and ERA-40 [*Monaghan et al.*, 2006a] match the in situ accumulation data quite well. There are no observational records of precipitation over sea ice with which to assess the ERA-40 data, other than at a very few isolated and short-term drift stations. However, several studies have compared other atmospheric variables with observations from coastal stations, ships, and drifting buoys. During the satellite period (post 1979), the performance of ERA-40 as compared to data from coastal stations is excellent [*Bromwich and Fogt*, 2004]. In addition, the ECMWF operational analysis has been shown to perform quite well [*Cullather et al.*, 1997; *King*, 2003]. The magnitude and overall pattern of annual snowfall over the Southern Ocean generally agrees with estimates of P-E reported by *Cullather et al.* [1998]. Therefore we have some degree of confidence that despite the lack of validation data, the ERA-40 snowfall record is a reasonable representation of the true snowfall. Whether this is true will be assessed below.

[15] To examine regional variability, the Southern Ocean is divided into four sectors, following *Gloersen et al.* [1992] (Figure 1). For this paper, we have combined their Western Pacific and Indian Ocean Sectors into a single East Antarctic sector.

2.2. Snowfall and Snow Depth Variability

[16] The mean September snow depth for the 23-year period 1979–2001 shows the deepest snow occurring in the northwestern Weddell Sea and along the West Antarctic Coast from the Bellingshausen to Ross seas (Figure 2a) where there are substantial quantities of multiyear ice, which generally has very deep snow [*Jeffries et al.*, 1994; *Massom et al.*, 1997]. The thinnest snow is found in the East Antarctic sector. The overall average is 15 cm. Snow accumulation (defined here as total snowfall that falls over ice-covered seas between March and September) shows a similar pattern (Figure 2b) with high accumulation along the Amundsen Sea coast and the outer Ross Sea, and low accumulation in the Eastern Weddell and the inner Ross Sea. The most notable difference is in the East Antarctic, where some of the highest snowfall rates occur where the snow depth is the lowest. The difference in the western Weddell Sea is attributable to drift of multiyear ice in the northern arm of the Weddell Gyre. Also striking is the discrepancy between mean accumulation and snow depth, with a mean accumulation of 69 cm, or over 4 times the observed snow depth. This difference is due to at least two factors: snow-to-ice conversion through surface flooding

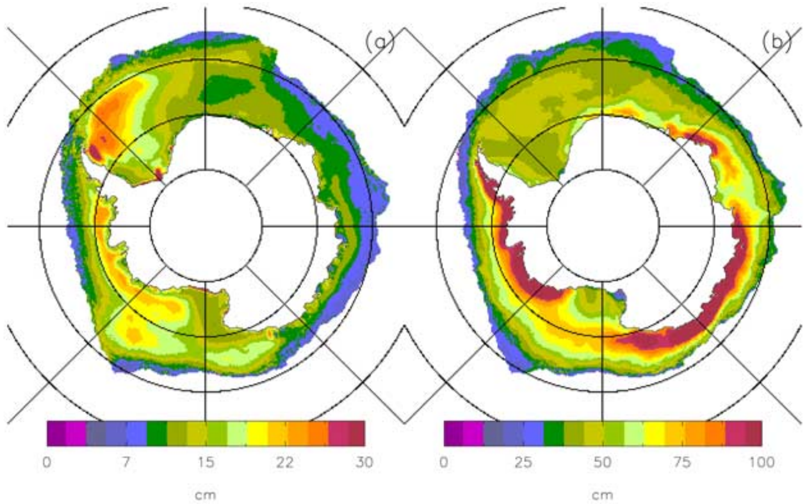

Figure 2. (a) Mean September satellite snow depth and (b) accumulation from ERA-40 snowfall. Accumulation is defined here as cumulative snowfall (March–September) that falls on sea ice. The most striking difference is in the East Antarctic sector, where the highest accumulation rates are accompanied by the lowest snow depths.

and freezing, and reduction in mean snow depth through ice divergence and new ice growth (which will initially have zero snow depth). Redistribution and removal of snow through aeolian transport could also be important [*Eicken et al.*, 1994].

[17] Between 1979 and 2001, there have been small but significant trends toward increasing snow depth in winter for all regions except the Amundsen/Bellingshausen, where a decline in snow depth has occurred (Figure 3a). This has also been noted in the shorter record analyzed by *Markus and Cavalieri* [2006]. Note that here and for all subsequent calculated trends or regional averages, only pixels that are ice-covered for the entire 23-year record are included to reduce any biases due to variations in ice extent. For regional average trends any effect is generally small. The trend in the Weddell Sea appears to be largely attributable to a change in multiyear ice distribution. Although the trends are significant, they represent at most a 4 cm increase in mean winter snow depth over the study period. The inter-annual variability is quite low, with a standard deviation of the regional means of only 1 to 2 cm.

[18] The mean winter snowfall on the other hand shows no significant trends (Figure 3b). The difference, if the snow depth trends are real, must then be either due to the timing of sea ice growth (which would affect the accumulation period), or trends in the amount of snow-to-ice conversion. Comparing trends in mean September snow depth (Figure 4a) and mean September accumulation (Figure 4b) suggest that it is at least partly the former. The largest trends in both snow depth and accumulation in the Ross Sea (positive trend) and Bellingshausen Sea (negative trend) are well correlated (note the difference in location is in part because the effects of ice drift, implicit in Figure 4a, are not accounted for in Figure 4b). The difference between Figure 3 and Figure 4 is somewhat subtle: If the mean snowfall over sea ice is constant over all months, but the rate of expansion of winter sea ice quickens, then both the accumulation and snow depth will increase as there is more time for snow to fall on

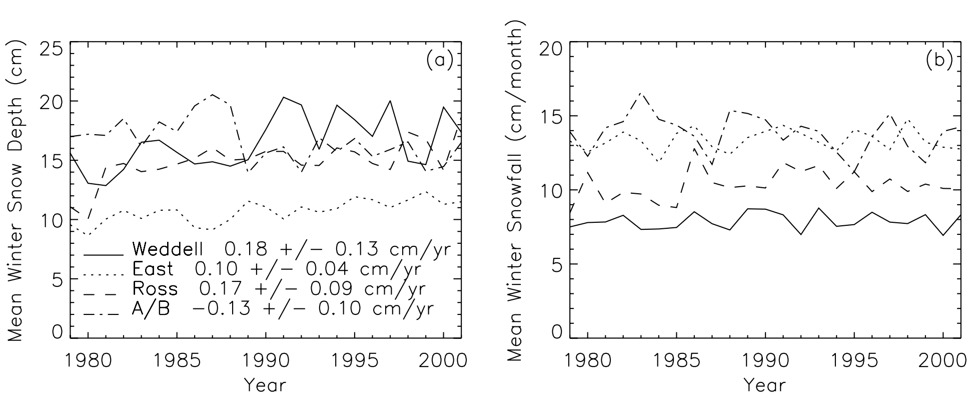

Figure 3. Annual trends for (a) mean winter (April–September) snow depth and (b) winter snowfall (expressed as cm/month). There are small but significant trends in snow depth, but not for snowfall (uncertainty determined using a two-sided t-test at the 95% criterion).

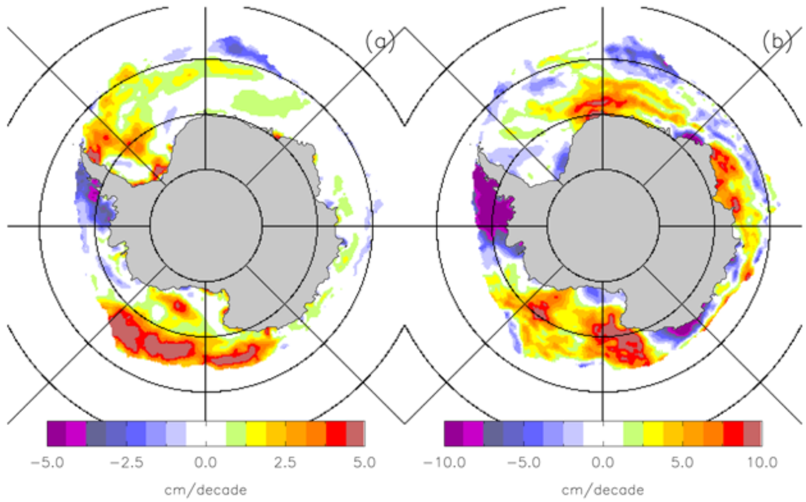

Figure 4. Annual trends for (a) September snow depth and (b) September snow accumulation (no snow-to-ice conversion). Trends are apparent for total September accumulation in the Bellingshausen and outer Ross seas which appear to coincide with snow depth trends (accumulation has not been corrected for ice drift).

a given piece of ice. Some caution in interpreting these trends is warranted; trends in snow depth might also reflect physical changes in the character of the snow pack due to changes in environmental forcing. Spurious trends in ERA-40 snowfall are also possible, although *Monaghan et al.* [2006b] suggest that the interannual variability in ERA-40 is well captured.

2.3. Methodology

[19] The amount of snow to ice conversion can be estimated by determining what fraction of the snowfall does not contribute to the deepening of the mean snow depth within a given pixel. Given a map of satellite snow depth for a given month, an initial estimate for the snow depth for the following month is predicted by advecting the snow cover using the monthly-mean ice drift. Near the ice edge, where determination of ice drift velocity is difficult, the drift is extrapolated from the nearest available vector within the interior pack. Where convergence occurs the snow depth is scaled by the areal fraction of ice advected into the pixel to prevent nonphysical increases in snow depth (snow does not "ridge" like ice; the mean snow depth averaged over all ice should be roughly the same before and after convergence. This assumption is debatable, but reasonable given the simple model used here.). The new snow depth can then be estimated by

$$h_{new} = h_{adv} + P\frac{(C_{new} - \Delta C)}{C_{new}} + P\frac{\Delta C}{2C_{new}}, \qquad (1)$$

where h_{new} is the predicted snow depth for the current month, h_{adv} is the initial snow depth estimate, P is the monthly mean snowfall, C_{new} is the current ice concentration, and ΔC is the difference between the current ice concentration and the previous months concentration after it has been advected. ΔC provides an estimate of the fraction of new ice in a given pixel. This is set to zero for converging conditions. The second term in (1) is divided by two because on average, the new ice will exist for only half the month, and so only receive half the precipitation. To reduce errors due to ice drift or inaccurate snow depth retrieval near the ice edge, we only include pixels that were ice-covered for both the current and previous month in all subsequent analysis.

[20] By subtracting the observed snow depth from the predicted snow depth, we obtain the excess snow, or the amount of snow that must be converted to snow ice. While simple, this method has the advantage that the results do not depend on the particulars of the snow or ice thickness distributions within a pixel. The results show that there is excess snow in all regions and all months of the growth season (Figure 5), but varying from near zero in May in the Weddell Sea, to 12 cm in October in the East Antarctic sector. The seasonal cycle of snow depth is perhaps surprisingly weak considering the fairly constant snowfall of about 10 cm per month (Figure 6). Much of the reason is snow-ice formation, as mentioned above. The second effect,

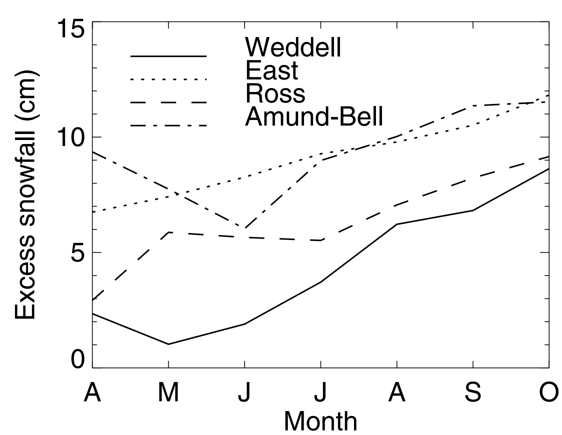

Figure 5. Mean monthly excess snowfall (predicted-observed) for each region.

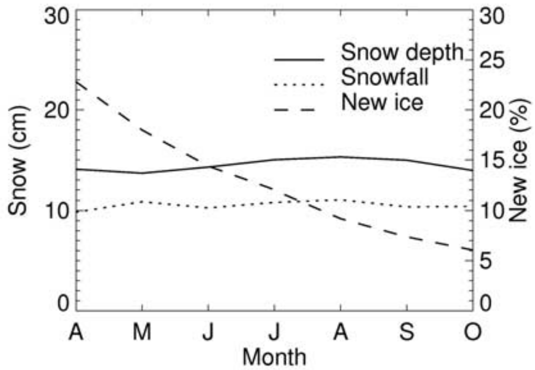

Figure 6. Seasonal cycle of snow depth, snowfall, and new ice.

growth of new snow-free ice, is also important. New-ice formation, given by ΔC decreases from over 20% to less than 10% of areal coverage through the season (Figure 6). Given a mean snow depth of 15 cm, this accounts for a drop of about a few centimeters in snow depth month to month. The decrease in new-ice production throughout the growth season shows that ice divergence cannot be responsible for the decline in mean snow depth in September and October (Figure 6). In fact both the mean excess snow and snowfall are about 10 cm by October, indicating that practically all new snowfall is converted into snow ice.

3. Snow-Ice Formation

[21] To determine the cumulative snow-ice thickness, the snow ice is allowed to advect in the same manner as the snow. It is treated similarly under converging conditions. This means we are neglecting dynamic thickening of snow ice in ridges. The snow-ice thickness is then an indicator of the amount of snow ice found in level ice and so is more directly comparable to sea ice structure data from ice cores, which are primarily obtained from level ice. The calculated snow-ice thickness then gives an underestimate of the total snow-ice volume. Because of the possibility of errors in the spatial distribution of snowfall for a given month, negative values of snow-ice production are retained, so that after several months of accumulation, the regional mean snow-ice thickness will be unbiased.

[22] To determine the amount of excess snow converted to snow ice, we must make an assumption about how much the snowpack compacts and settles when flooded. *Maksym and Jeffries* [2000] assumed no compaction occurs during flooding and freezing, so the snow-ice thickness would equal the excess-snow thickness. Field observations of slush salinities and δ^{18}O values suggest that slush typically consists of 50% snow crystals and 50% seawater or brine [*Crocker and Wadhams*, 1989; *Eicken et al.*, 1995; *Lytle and Ackley*, 1996; *Jeffries et al.*, 1997b]. We therefore assume that the snow density (of the ice fraction only) increases from 350 to 500 kg m^{-3} when flooded. This is a nontrivial point, as it reduces the thickness of snow ice formed by a factor of 0.7. The consequences of this assumption are examined below.

[23] Mean snow-ice thicknesses for June and September are shown in Figure 7. The strong seasonal and spatial variability is evident, with the thickest snow ice forming in East Antarctica and the Amundsen Sea. Comparison with the maps of snow depth and snow accumulation (Figure 2) show clearly that snow-ice thickness is most dependent on snowfall, and not on snow depth. The spatial distribution of snow-ice formation agrees qualitatively with ice core data from the Weddell, Ross, Bellingshausen, and Amundsen seas [*Jeffries et al.*, 2001; *Eicken et al.*, 1994; *Lange et al.*, 1990]. Particularly encouraging is the spatial variability within the Ross and Weddell seas generally matches inferences from field observations [*Jeffries et al.*, 2001; *Eicken et al.*, 1994]. However, it appears to be at odds with field data from the East Antarctic [*Worby and Massom*, 1995; *Worby et al.*, 1998]. This is explored further in section 3.2.

3.1. Snow-Ice Variability

[24] The interannual variability of snow-ice thickness is dominated by the variability in snowfall. Figure 8a shows the annual snow-ice thickness anomaly versus snow accumulation anomaly for September of each year and each region. Between 34 and 72% of the variance in snow-ice

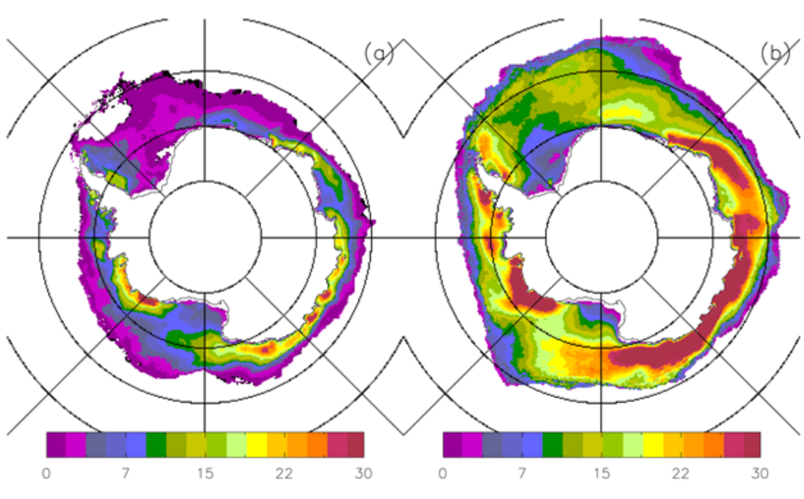

Figure 7. Mean snow-ice thickness in (a) June and (b) September.

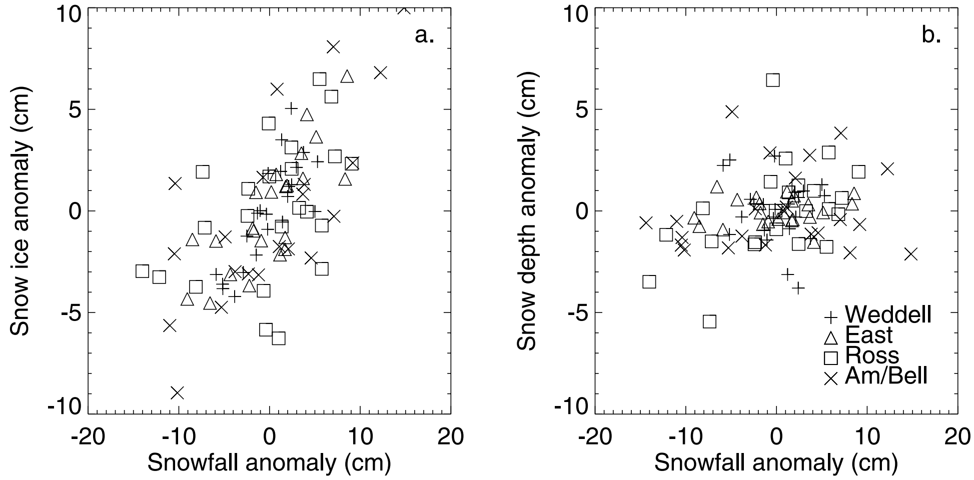

Figure 8. Dependence of September snow ice and snow depth on snowfall. Each symbol represents the anomaly for a given year for each of the five regions. (a) Snow ice versus snowfall and (b) snow depth versus snowfall. Most of the variability in snow-ice thickness is explained by changes in snowfall, but this relationship is entirely absent for satellite snow depth.

thickness is explained by variability in accumulation for all regions except the Ross Sea, where surprisingly, there is no significant correlation. In contrast, there is no significant relationship between snow depth and accumulation (Figure 8b), except in the Ross Sea, where there is a weak positive correlation, consistent with Figure 4. Snow depth is also uncorrelated with snow-ice thickness (not shown). This result is somewhat surprising, and could call into question the ability of satellite snow depth retrievals to resolve interannual variability. Note that when snow-ice formation is widespread, most of the new accumulation is converted to snow ice. In extreme cases, snow depth has been observed to decrease [*Lytle and Ackley*, 2001]. Thus temporal variability in satellite snow depth due to variations in snow physical properties could overwhelm the variability due to snow depth itself.

[25] Trends in September snow-ice thickness are near zero or slightly negative for each region, although most are not significant (Figure 9a). The exception is for the Amundsen and Bellingshausen sector, where there is a strong negative trend, corresponding to the negative trend in accumulation (Figure 4b). These trends are possibly linked to the decrease in ice extent reported in this region [*Zwally et al.*, 2002a], although the trends are inconsistent with the link hypothesized by *Jacobs and Comiso* [1993] and *Jacobs and Comiso* [1997].

[26] Interestingly, the interannual variability in snow-ice thickness is much higher than either snow depth or snow accumulation (roughly doubled, as a percentage of thickness). This is largely due to variability in ice drift and divergence and the resulting production of new, snow-free ice. New-ice production shows a striking positive trend for all regions but the Weddell (Figure 9b). New-ice production acts to reduce the mean snow-ice thickness for level ice directly (although not necessarily the contribution of snow ice to the total ice volume), and indirectly by reducing the area-averaged snow depth, thus reducing calculated excess-snow thickness and hence snow-ice production. This is reflected in the variability in September snow-ice thickness, with winter new-ice production explaining on average 33%

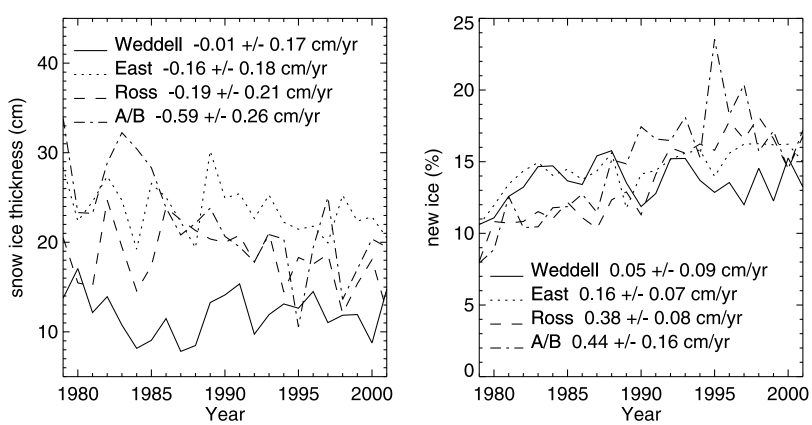

Figure 9. Trends in (a) September snow-ice thickness and (b) mean winter (April–September) new ice production. Strong trends in new ice production for all regions except the Weddell coincide with decreases in snow-ice production.

Table 1. Comparison of Modeled and Observed Snow-Ice Thicknesses[a]

			Observations			Modeled				
Region	Cruise	Date	Mean Core Thickness	Meteoric Ice Thickness[b]	Snow Ice Thickness[c]	Standard	Regional Mean	Including Snow Drift	High Divergence	Without Settling
Weddell[d]	WWSP86	July–Sept 1986	88	6	15	8	8	5	3	13
	WWGS89	Sept–Oct 1989	97	9	22	14	14	10	8	22
East[d]	V1 92/93	Oct 1992	65	7	17	30	30	24	21	44
	V9 92/93	April 1993	26	1	3	5	8	5	4	9
Ross[d]	NBP95-3	May–June 1995	57	5	14	11	8	9	8	16
	NBP95-5	Aug–Sept 1995	66	7	18	15	17	14	11	22
	NBP98-3	May–June 1998	54	6	8	5	8	4	8	11
Am/Bell[d]	NBP93-5	Sept–Oct 1993	86	5	19	16	25	11	9	24
	NBP94-4	Aug–Sept 1994	74	9	28	12	20	9	5	18
	NBP95-5	Aug–Sept 1995	84	6	20	10	20	6	4	15
Mean			70	6	16	13	16	10	8	19

[a]Units are centimeters.
[b]Meteoric ice thickness includes both the total meteoric ice component and a seawater fraction.
[c]Snow-ice thickness is the total ice thickness that includes at least some meteoric component.
[d]Observational data are calculated from *Lange et al.* [1990] and *Eicken et al.* [1994] for the Weddell Sea, *Worby et al.* [1998] for the East Antarctic, and *Jeffries et al.* [1998a, 2001] for the Ross, Amundsen, and Bellingshausen seas (see text for details).

of the variability. The importance of the second (indirect) effect is unclear, since increased production of new, thinner ice could potentially lead to increased snow-ice formation for high accumulation rates. Conversely, by reducing the areal coverage of deeper snow with already high flooding potential, it could lead to a reduction in the area-averaged snow-ice production. Without a physical ice growth model, we cannot evaluate this effect in this study.

3.2. Comparison With Ice Core Data

[27] We compare derived snow-ice thickness to estimates from ice core analysis from nine cruises that took place between April and October. The location, cruise name, dates, and sources are given in Table 1. We exclude other reports of snow ice from isolated observations [e.g., *Lytle and Ackley*, 2001] or cruises where few cores were analyzed (cruises V1 and V2 91/92) [*Worby et al.*, 1998]. Each of these cruises comprise 20 or more ice cores. Determination of snow-ice thickness from these data is problematic, however. Typically, snow ice is identified by its δ^{18}O signature [e.g., *Ackley et al.*, 1990; *Lange et al.*, 1990; *Eicken et al.*, 1994; *Jeffries et al.*, 1997b, 1998b, 2001; *Worby and Massom*, 1995], where a negative δ^{18}O generally indicates at least some meteoric-ice (snow) component. Most authors have defined snow ice as ice having at least some meteoric ice [*Jeffries et al.*, 1997b, 1998b, 2001; *Worby and Massom*, 1995], while others report only the meteoric component [*Lange et al.*, 1990; *Eicken et al.*, 1994]. The difficulty with the first approach is that the highly negative δ^{18}O "fingerprint" of snow found in sea ice cores tends to reduce with depth [*Lange and Hubberten*, 1992; *Maksym and Jeffries*, 2001] making the boundary between snow ice and frazil indistinct. This has been attributed to vigorous brine convection during freezing [*Maksym and Jeffries*, 2001; *Lytle and Ackley*, 2001].

[28] Choice of slightly different criteria for classification of snow ice can lead to vastly different estimates of the contribution of snow to the thickness of sea ice [*Jeffries et al.*, 1997b; *Maksym*, 2001]. *Lange et al.* [1990] take a different approach and derive the combined total meteoric and seawater fraction of the ice core. This approach is conceptually more satisfying, since it is conservative with respect to meteoric ice and reduces the possibility of misclassifying frazil as snow ice due to downward migration of δ^{18}O-depleted brine, yet also accounts for the seawater that would flood the snow and freeze. However, it will underestimate the snow-ice fraction if some of the δ^{18}O-depleted brine leaves the ice. Here we will form two distinct definitions: "Snow ice" is defined to be sea ice that has at least some meteoric component, while we will define "meteoric-ice thickness" as an equivalent thickness of ice formed from the total snow and seawater component of the sea ice core based on isotopic analysis. This should be roughly equal to the original thickness of the slush layer (50% snow and 50% seawater) before freezing and any redistribution of meteoric ice within the ice core. The meteoric-ice thickness can then be regarded as a lower bound for the amount of snow-to-ice conversion found in level Antarctic sea ice, while the snow-ice thickness forms an upper bound.

[29] Table 1 contains the two estimates for snow-ice thickness and meteoric-ice thickness from the observations. Most authors report these quantities as a fraction of the total ice thickness. Here we have converted all values to thicknesses using reported mean ice core thicknesses. *Jeffries et al.* [2001] report snow-ice thickness and meteoric-ice fractions (i.e., f_m, or snow only) for the Ross, Amundsen and Bellingshausen seas, while for East Antarctica, *Worby et al.* [1998] report only snow-ice thickness, and for WWGS89, *Eicken et al.* [1994] report only meteoric-ice fractions. Only *Lange et al.* [1990] report both a meteoric-ice thickness and meteoric-ice fraction for WWSP86. We use this to derive a scaling for meteoric fraction to meteoric-ice thickness. Meteoric-ice thicknesses for the WWSP86 and all cruises in the Ross, Amundsen, and Bellingshausen seas are then estimated by scaling the reported meteoric-ice fraction. Snow-ice thickness for WWGS89 and meteoric-ice thicknesses for East Antarctica are then estimated by assuming the same ratio of snow-ice thickness to meteoric-ice fraction reported by *Jeffries et al.* [2001].

[30] The in situ data for each cruise are compared to the modeled snow-ice thickness by computing the mean snow-ice thickness for all pixels that fall on the respective cruise track after first smoothing the modeled data to a 100 km

grid. The modeled snow-ice thicknesses (“standard”' case, column 7 of Table 1) generally fall between these two bounds. The exception being in the East Antarctic, where there is excessive snow-ice production. For the other sectors, which criterion provides the better fit varies by region. Note that while in the Amundsen/Bellingshausen the observed snow-ice thickness is significantly higher than for the standard model run, this may be due to an error in spatial distribution of ERA-40 snowfall. On all cruises in this region the ship did not penetrate close to the coast where the thickest snow ice is predicted to form. Taking the mean snow-ice thickness over the entire region and study period (eighth column in Table 1) provides a much closer match to the observed snow-ice thicknesses.

[31] Aside from errors in the snowfall forcing, there are several sources of error that could affect our estimates of snow-ice thickness. Loss of snow to leads via aeolian transport has been examined by *Eicken et al.* [1994] who suggest that as much as 10 cm of snow can be lost due to snow drift. *Sturm et al.* [1998] argue that the snow can be locked up by the formation of hard crusts, limiting snow drift losses. The ubiquity of surface drift features [*Massom et al.*, 2001] suggest that there is at least some aeolian transport and hence must be some loss to leads. To assess this, following *Eicken et al.* [1994], we repeated the analysis assuming that roughly 10 cm of snow is lost during the windy winter months, or 2 cm per month. Somewhat surprisingly, this results in only a modest reduction in snow-ice thickness (ninth column of Table 1). This is largely because only some of the total snow-ice thickness accumulates over the full winter period. By September, much of the level ice cover is only a few months old. Note that this scenario is also roughly equivalent to a 20% reduction in precipitation.

[32] A second possible source of error is that new ice production is underestimated by the monthly-mean divergence from SSM/I ice motion data. *Geiger et al.* [1998] and *Heil et al.* [2001a] show that neglecting high-frequency motion can significantly underestimate the total ice deformation. We therefore compute the snow-ice thickness if the new-ice production rate were doubled (which would amount to 20–40% areal coverage of new ice each month), which we label “high divergence.” This greatly reduces the computed snow-ice thickness (tenth column of Table 1) close to the lower bound estimate from the in situ data. Clearly, ice motion and deformation need to be determined accurately in order to better constrain estimates of snow-ice production.

[33] Finally, we note that these estimates rely on the assumption that the snowpack settles significantly when flooded with seawater. If it does not, then snow-ice thickness estimates will be about 40% larger (last column of Table 1). Without settling, the modeled snow-ice thickness matches the observed snow-ice thickness quite well, with the exception of East Antarctica. This must be viewed as an upper bound for snow-ice thickness for both in situ and model estimates.

4. Deriving Ice Thickness

[34] As a result of the balance between the insulating effect of the snow cover and the growth-limiting effects of high ocean heat flux, mean freeboards (height of the ice surface above sea level) are often near zero [*Adolphs*, 1998; *Jeffries et al.*, 1998b]. When this occurs, ice thickness is largely determined by the snow depth. Several authors have noted a strong relationship between mean snow depth and mean ice thickness on Antarctic ice floes [*Worby et al.*, 1996; *Jeffries et al.*, 1998b], suggesting the possibility of estimating ice thickness from observations of snow depth.

[35] For an ice floe in hydrostatic equilibrium, the snow depth can be related to the ice thickness by

$$\rho_s h_s + \rho_i h_i = \rho_w h_i - \rho_w fb, \tag{2}$$

where $\rho_{s,i,w}$ denotes the density of snow, ice and seawater, respectively, $h_{s,i}$ is the snow or ice thickness, and *fb* is the freeboard. Rearranging, we get

$$h_i = \frac{\rho_s}{(\rho_w - \rho_i)} h_s + \frac{\rho_w}{(\rho_w - \rho_i)} fb. \tag{3}$$

When flooding and snow-ice formation occur, the freeboard is zero, thus given reasonable values for snow and ice densities, a measurement of snow depth can be used to estimate the ice thickness where snow ice is predicted to form. In the following sections, we use (3) to derive level ice thicknesses where excess snowfall, and thus snow-ice formation, is observed. These results are compared to ship-based observations of level ice thickness. Sources of error and their impact on the estimates are discussed, and finally, the interpretation of derived ice thicknesses in comparison with other methods is discussed.

4.1. Methodology

[36] To determine ice thickness reliably using (3), we need accurate estimates of snow, ice, and seawater densities. For seawater, ρ_w = 1028 kg m^{-3} for a mean seawater salinity of 35 psu. Variability in ρ_w due to salinity variations is low, resulting in less than one percent error in ice thickness. There are very few reliable measurements of Antarctic sea-ice density. Here we use 915 kg m^{-3}, which has been measured for first-year landfast ice near Syowa station and in McMurdo Sound [*Matsuo and Miyake*, 1966; *Pringle et al.*, 2006]. This is consistent with measurements on first-year Arctic ice [*Weeks and Lee*, 1958; *Schwerdtfeger*, 1963; *Nakawo*, 1993]. This matches theoretical estimates for sea ice with a gas content of about 1.5%, which is consistent with most measurements which suggest a typical range of about 0.5–2% [e.g., *Nakawo*, 1993; *Tison et al.*, 2002]. While snow ice might have a significantly higher gas content [*Weeks and Lee*, 1958; *Leppäranta*, 1983; *Crocker and Wadhams*, 1989], it will generally comprise a relatively small portion of the total ice volume. Therefore we suggest 915 kg m^{-3} to be a fairly accurate estimate and with low variability on a 100-km spatial scale (perhaps ±10 kg m^{-3}). If a significant fraction of the ice thickness comprises bubbly ice (i.e., snow ice, pancakes, or multiyear ice), then the computed ice thickness will be significantly overestimated.

[37] Snow density in autumn and winter has a wide range of values, from 108 to 760 kg m^{-3} [*Sturm et al.*, 1998], but as much of this variability occurs on small scales the large-scale variability is significantly reduced to between 250 and

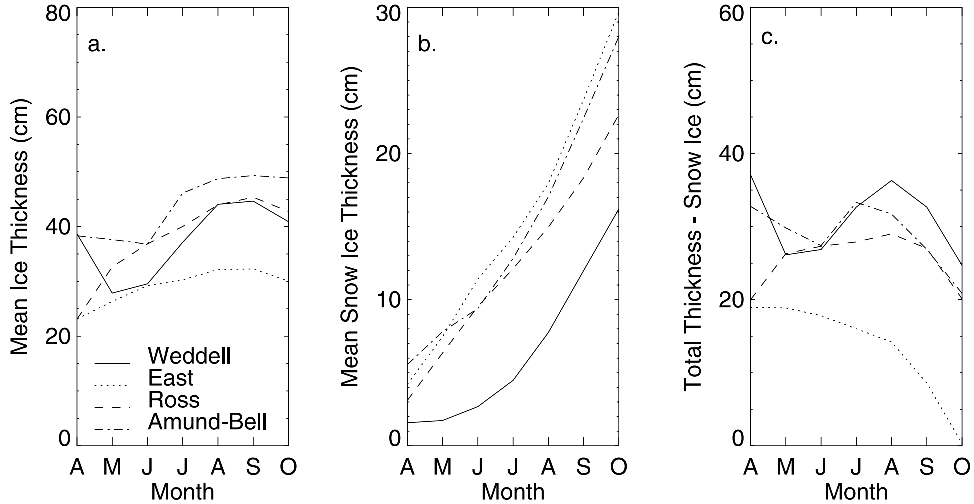

Figure 10. Mean seasonal variability in (a) derived ice thickness, (b) snow-ice thickness, and (c) total thickness minus snow-ice thickness, which represents the remainder of the ice thickness that is composed of frazil and congelation ice.

390 kg m^{-3}, with a mean of about 350 ± 50 kg m^{-3} [*Massom et al.*, 2001]. Inserting these densities into (3), we get

$$h_i = (3.10 \pm 0.52)h_s + (9.10 \pm 0.81)fb. \quad (4)$$

[38] For each 100 km × 100 km pixel where the predicted monthly mean snow depth is greater than the satellite snow depth (i.e., snow-ice forms), we assume that the mean freeboard is zero. (This is not necessarily the case; as is clear from (4) this can cause substantial errors for large freeboards. The implications of this are discussed below.) Ice thickness is determined only for those pixels where snow-ice forms. As noted above, the calculated ice thickness is assumed to be that for level ice only (see below for justification).

4.2. Ice Thickness Estimates

[39] Mean ice thicknesses for each sector closely mimic the spatial distribution and seasonal pattern of snow depth (Figure 10a). This is not surprising given the use of (4) and the fact that snow-ice formation is widespread throughout the growth season; snow ice is predicted to form at approximately 60% of pixels in June and more than 90% in September. The 23-year mean ice thickness is almost identical to the snow depth in Figure 2 except for the factor of 3.10 from (4). Ice is thickest in the Amundsen/Bellingshausen seas, reaching a mean of 49 cm in September, and thinnest in the East Antarctic sector, reaching a mean of 31 cm. There is substantial interannual variability (roughly 3 times the snow depth variability in Figure 3). The rather weak seasonal cycle is supported by field measurements [*Adolphs*, 1998; *Jeffries et al.*, 2001; *Worby et al.*, 1998]. Generally, however, mean ice thicknesses are about 15 cm below those from ice core or drilling data (see Table 1).

[40] The contribution of snow ice to the total thickness shows a strong seasonal trend (Figure 10b). Snow ice comprises on average 23% of the thickness in June, comparable to estimates from the Ross Sea [*Jeffries et al.*, 2001] (Table 1). However, this increases to 43% by September, which is higher than any estimates from ice core data. As noted above the modeled snow-ice thicknesses may be reasonable, so clearly the ice thickness is underestimated. Subtracting the snow-ice thickness from the total thickness gives an estimate of the ice thickness that is due to other growth processes (frazil and congelation) (Figure 10c). This shows a decline in the frazil and congelation thickness in late winter. While several studies show that the high ocean heat flux and accumulation rate can produce such an effect through combined basal melting and snow-ice growth [e.g., *Jeffries et al.*, 2001; *Lytle and Ackley*, 2001; *Maksym and Jeffries*, 2000], ice core evidence suggests that the actual contribution of frazil and congelation to the total ice thickness is significantly larger in late winter than Figure 10c suggests [*Jeffries et al.*, 2001].

[41] The anomalously low frazil and congelation component is particularly apparent in the East Antarctic, where Figure 10 indicates that over 90% of the total ice thickness comprises snow ice. Note that these are regional averages; in some areas of heavy snowfall the predicted snow-ice thickness is greater than the total thickness. This is particularly true for the coastal areas near Mawson and between Casey and Dumont D'Urville along the coast of East Antarctica, and to a lesser extent along the coast of Marie Byrd land in the Amundsen Sea (see below). While this can occur where snow-ice growth occurs in conjunction with basal melting [*Lytle and Ackley*, 2001], widespread occurrence throughout East Antarctica is highly unlikely given the widespread observation of significant quantities of both frazil and congelation ice [*Worby et al.*, 1998]. It is most likely that there is an underestimate of ice thickness (possibly due to a low bias in satellite snow depth retrievals), an overestimate of snow accumulation, or both. It should be noted, however, that while this is clearly true for East Antarctica between Mawson and Casey where there have been several observations of sea ice structure that contradict this [*Jacka et al.*, 1987; *Allison and Worby*, 1994], the other areas have been largely unvisited in winter. *Jeffries et al.*

Table 2. Comparison of Satellite-Derived and ASPeCt Ice Thickness Data for August–October[a]

Region	Snow Depth		Ice Thickness		Freeboard		SSM/I Ice Thickness		
	ASPeCt	SSM/I	AsPeCt	SSM/I	ASPeCt	Apparent	Regional Average	Including Bias Correction	From Snow Depth Decrease
Weddell	15	15	57	42	1.2	1.3	43	53	48
East	12	10	46	32	1.0	1.5	31	43	34
Ross	18	20	50	59	−0.5	−1.6	44	70	46
Am/Bell	18	15	53	48	−0.7	0.4	49	59	46
Antarctic Mean	15	14	51	42	0.4	0.7	41	53	43

[a]Units are centimeters.

[1994] report ice cores taken in austral summer along the Amundsen Coast with more than two meters of fine grained ice with negative δ^{18}O values, suggesting that substantial quantities of snow ice may occur.

[42] To validate the ice thickness product, we compare satellite-derived ice thicknesses to shipboard observations from the Antarctic Sea ice Processes and Climate (ASPeCt) program of the Scientific Committee on Antarctic Research [*Worby and Allison*, 1999]. This data set is derived from routine underway observations of snow and ice thickness taken from over 40 voyages in the Antarctic ice pack. For the time period chosen, this comprises observations taken almost entirely between 1992 and 2001. The ASPeCt snow depth and level-ice thickness have been gridded to the SSM/I grid for each month and year. Multiple observations within a single pixel were averaged. The satellite-derived snow and ice thickness (smoothed to 100 km) were extracted for each pixel that had coincident observations. Then the average snow and ice thicknesses for both modeled and observed data were determined for each sector. Note that the shipboard observations are estimates of level ice thickness, and exclude ridged ice, which is difficult to estimate from underway observations. We use this rather than correct for ridging, since the satellite snow depths are likely an estimate of snow depth on level ice for several reasons: (1) The original snow depth algorithm was derived in part using ASPeCt data, (2) the satellite measurements appear to underestimate snow depth in heavily deformed areas [*Worby et al.*, 2008], and (3) ridged ice typically has high freeboard, but not necessarily larger snow depths than neighboring level ice. *Markus and Cavalieri* [1998] show that the snow depth algorithm cannot distinguish snow depths greater than about 50 cm, so very thick snow that forms drifts in the vicinity of ridges will tend to be underestimated by the algorithm. Thus we argue that the mean satellite snow depth most closely reflects the mean snow depth over level ice, for which freeboards are typically near zero by late winter [e.g., *Jeffries et al.*, 1998b].

[43] Table 2 gives a comparison between the ASPeCt and satellite-derived snow and ice thicknesses for each region for August through October. The snow depth compares remarkably well, given that most of this data was not used in the original algorithm development [see also *Markus and Cavalieri*, 1998, Figure 8]. The largest difference is in the Amundsen/Bellingshausen sector where the observed snow depth is 3 cm greater than the satellite estimate. Overall, the bias is about 1 cm, which is substantially lower than the 3.5 cm bias reported by *Markus and Cavalieri* [1998]. The difference is attributable to the somewhat different areas selected for comparison [see *Markus and Cavalieri*, 1998, Plate 3], and many of the in situ data sets used by *Markus and Cavalieri* [1998] are from drilling data, which tend to be biased toward deeper snow and thicker ice relative to the shipboard observations [*Adolphs*, 1998].

[44] Ice thicknesses compare reasonably well (fourth and fifth columns of Table 2), but there is a systematic bias in the satellite ice thickness with a mean bias of −9 cm. The error is most pronounced in the East Antarctic sector, in large part owing to bias in the satellite snow depths. Likewise, the ice thickness in the Ross sea is overestimated for a similar reason. Some of the discrepancy between in situ and satellite ice thickness in the Weddell Sea might be attributable to the substantial fraction of second-year ice encountered on many of the voyages [e.g., *Eicken et al.*, 1994]. The possibility of sampling bias, either spatially or temporally, can be examined by comparing these results with averages over each region for the entire 23-year period (eighth column of Table 2). The differences are generally small, the lone exception being the Ross Sea where the thin ice close to the Ross Ice Shelf has no in situ data for late winter.

4.3. Errors in Ice Thickness Estimates

[45] The accurate determination of ice thickness relies on an accurate estimate of snow depth when the freeboard approaches zero. This is fraught with a number of substantial sources of error which include, in relative order of importance (1) nonzero freeboard, (2) bias in snow depth retrievals, (3) uncertainty in timing of snow-ice formation (e.g., due to an overestimate of snowfall), (4) uncertainty in snow and ice density, and (5) precision of the snow depth retrieval algorithm. Below we discuss each of these issues.

[46] A nonzero mean freeboard is perhaps the largest source of error in regional-scale ice thickness determination. This is apparent from (4), which shows that ice thickness will be underestimated by almost 10 cm for every centimeter of freeboard. While freeboard must be locally below zero to form snow ice, this is not necessarily a good indicator of the larger-scale freeboard. While the detection of excess snow (Figure 5) indicates snow-ice formation within the SSM/I footprint, this only requires that some fraction of the freeboard distribution be less than or equal to zero. This is evident in the work of *Jeffries and Adolphs* [1997], where 29% of freeboards measured in the Ross Sea in early Winter, 1995 were less than zero, but the mean freeboard was 1.5 cm. By late winter, mean freeboards in the Ross, Amundsen and Bellingshausen seas tend to be near zero [*Adolphs*, 1998; *Jeffries et al.*, 1998b], although there is

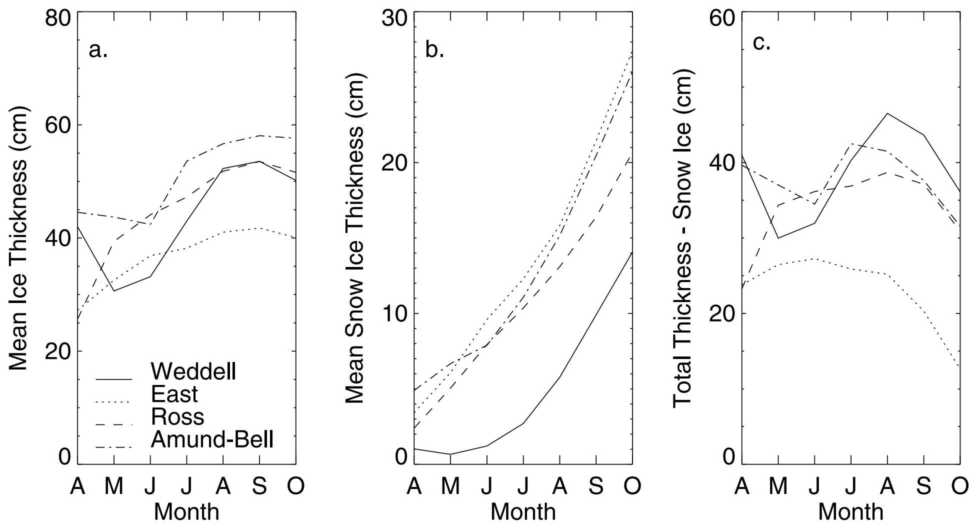

Figure 11. Same as Figure 10, but including a correction for the possible 3.5-cm bias in satellite snow depth.

some interannual variability. Mean positive freeboards of 1–5 cm have been observed in late winter in the Weddell Sea [*Wadhams et al.*, 1987; *Eicken et al.*, 1994]. Positive freeboards are also reported in the East Antarctic [*Massom et al.*, 1998]. Note, however, that this is at least in part due to the inclusion of ridged ice in the drilling data sets.

[47] To assess the effect of nonzero freeboard, we compare the mean freeboard for each region from the ASPeCt data (determined by (4)) with the apparent freeboard, defined as the freeboard required for the satellite-derived ice thicknesses to match the ASPeCt ice thicknesses using (4) (sixth and seventh columns of Table 2). This suggests that the mean freeboard is on the order of 1 cm, though somewhat higher in the Weddell and East Antarctic, consistent with lower snowfall there. Encouragingly, the apparent freeboards are a close match to the AsPeCt data, including the regional variability.

[48] The 3.5 cm bias noted in satellite snow depth retrievals [*Markus and Cavalieri*, 1998] may also contribute to the low values for derived ice thicknesses, although as noted above this bias appears to be significantly less in this study. If this bias is included, ice thicknesses are increased by about 11 cm, as expected from (4) (ninth column of Table 2). This produces more reasonable ice thickness throughout the growth season (Figure 11a). The effect on snow-ice thickness is small (Figure 11b), since the monthly change in snow depth is unchanged and so the excess precipitation is similar. The anomalously high contribution of snow ice to the total thickness noted above (Figure 10c) is ameliorated in most regions (Figure 11c). However, the problem still persists in the East Antarctic, suggesting that ERA-40 precipitation is too high in this region. *Bromwich et al.* [1995] notes that ECMWF operational analysis overestimates precipitable water at Dumont D'Urville by 40%. Note that the effect of a 3.5 cm bias in snow depth is roughly equivalent to a mean freeboard of 1 cm. This interpretation is more consistent with the data in the Weddell Sea and East Antarctic. It seems reasonable, then, that for level ice where flooding and snow-ice formation is widespread, that the large-scale mean freeboard is of the order 1 cm.

[49] The third source of error is related to the freeboard error, since accurate determination of ice thickness requires knowledge of when the mean freeboard within the SSM/I footprint approaches zero. In this study, there is substantial excess snow nearly everywhere by late winter, so the assumption of widespread flooding seems reasonable. However, this depends on the accuracy of the snow accumulation estimates (due to a combination of precipitation, snow drift, and ice divergence). An alternative method would be to identify those pixels where there is an unexplained drop in snow depth which may indicate flooding. The month-to-month change in snow depth, averaged over the 23-year period, shows a modest circum-antarctic rise in autumn and early winter (Figure 12), but by September, the snow depth begins to drop. This cannot be due to decreased snowfall or increased ice divergence (see Figure 6). An increase in snow wetness would cause an apparent drop in snow depth [*Markus and Cavalieri*, 1998], but temperatures are still generally well below freezing (note that the drop is more pronounced in the interior pack, where temperatures would be lowest). Therefore we attribute the drop to widespread flooding and snow-ice formation which removes some of the snow cover, and wets the base of the snow pack, reducing the apparent depth as seen by the satellite. Mean ice thicknesses obtained by only including pixels which see a drop in snow depth from August to September are given in the last column of Table 2. Overall, these are very similar to the regional means (eighth column of Table 2), suggesting that errors in precipitation have little impact on determination of ice thickness.

[50] Variation in the mean snow and sea ice densities is estimated to produce an uncertainty of about 17% in the ice thickness given by (4) averaged over the spatial scale of individual cruises. For a mean snow depth of 15 cm, (4) gives an uncertainty of about 8 cm, which is comparable to the difference between mean derived and in situ thickness. The high variability in snow density observed on individual

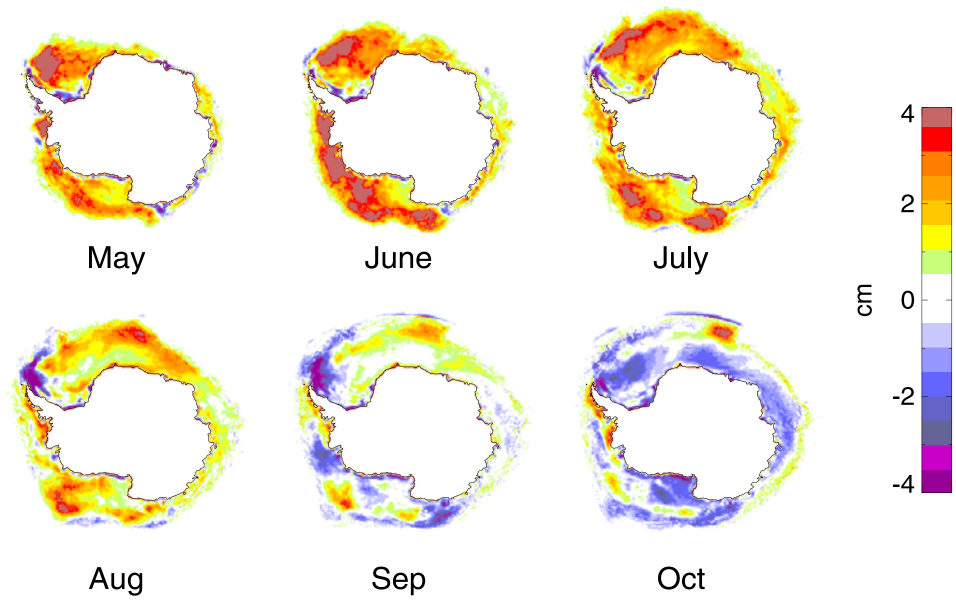

Figure 12. Monthly average change in snow depth. The change is calculated as the difference between the current month's snow depth distribution and the distribution predicted by advection of the previous month's snow depth.

cruises occurs on the floe scale or smaller, so on the scale of the SSM/I footprint, we do not expect the error to be much greater [*Sturm et al.*, 1998]. Note however, that substantial interannual variability can occur. For example, the mean snow density in late winter, 1993, in the Bellingshausen Sea was 247 kg m^{-3}, or about 100 kg m^{-3} less than in 1995 [*Massom et al.*, 2001]. For typical snow depths, this would lead to an overestimate of about 15 cm in ice thickness. However, this is ameliorated by several factors. First, the lower density snow reduces snow load, so the mean freeboard will tend to be higher. This causes an underestimate in ice thickness, so the two effects tend to cancel. Second, while the passive microwave algorithm is calibrated for snow depth, the effect of snow on microwave brightness temperature is due to scattering by snow grains [*Markus and Cavalieri*, 1998]; thus it is more properly a measure of snow water equivalent. A less dense snow cover will in general appear thinner than a dense snow cover.

[51] Snow densities may also be affected by sampling bias. High-density icy layers are common in snow on Antarctic sea ice, but these are generally not included in reported values for mean snow density. *Massom et al.* [1998] estimate that inclusion of icy layers will increase the mean snow density in the East Antarctic by 15%. This would increase the mean satellite ice thickness for the ASPeCt cruises from 42 to 48 cm, closely matching the shipboard estimate.

[52] Finally, we note that the precision of the snow depth algorithm is around 5 cm [*Comiso et al.*, 2003]. This gives an RMS error of 16 cm in derived ice thickness. At regional scales, however, this "random" error will likely be much reduced. Including only errors due to snow density and mean freeboard, we estimate the error in determination of level ice thickness from (4) to be about 10 cm, though the observed interannual variation in freeboard and snow density suggests that the accuracy for interannual comparison is on the order of 20 cm. It is difficult to estimate the overall error in ice thickness without a better understanding of the physical processes that affect the snow depth retrievals (i.e., owing to grain size or layering due to thaw/freeze cycles) [e.g., *Markus et al.*, 2006]. While various unmodeled processes can cause large errors at the pixel scale, for there to be substantial errors in large-scale means would require a systematic variation in snow properties interannually or regionally. Assuming an error in regionally averaged snow depth of 2 cm (based on results in Table 2), we estimate the overall error to be 10–20 cm (see below).

4.4. Comparison With Other Methods

[53] Given the relatively high errors in the derived ice thickness, it is worthwhile to compare this method with other promising satellite-based methods of determining Antarctic ice thickness, namely radar altimeters on the ERS and ENVISAT satellites [e.g., *Laxon et al.*, 2003], and the Geoscience Laser Altimeter (GLAS) on ICESat [*Zwally et al.*, 2002b]. The laser altimeter essentially gives a direct measure of the total freeboard (ice freeboard plus snow depth), while it is thought that the ERS and ENVISAT radar altimeters give a direct measure of the ice freeboard. In order to determine ice thickness, both of these methods require an independent estimate of snow depth. As the algorithm used in this study is currently the only available satellite-based estimate, these methods are subject to some of the same errors. In this section we compare the accuracy of passive microwave determinations of ice thickness with altimetric methods due to errors in snow depth estimates. This is intended as an illustrative exercise and not a precise estimate of the overall accuracy of any particular method.

[54] Following *Spreen et al.* [2006] the error in ice thickness from satellite snow depth can be determined from (2)

$$\sigma_{hi} = \left[\left(\frac{h_s}{\rho_w - \rho_i} \right)^2 \sigma_{\rho s}^2 + \left(\frac{\rho_s^2 h_s^2 + \rho_w^2 fb^2}{(\rho_w - \rho_i)^4} \right) \sigma_{\rho i}^2 + \left(\frac{\rho_s}{\rho_w - \rho_i} \right)^2 \sigma_{hs}^2 + \left(\frac{\rho_w}{\rho_w - \rho_i} \right)^2 \sigma_{fb}^2 \right]^{\frac{1}{2}}, \quad (5)$$

where $\sigma_{\rho s}$, $\sigma_{\rho i}$, and σ_{hs} denote the estimated errors in snow density, sea ice density, and satellite snow depth, respectively. The freeboard error, σ_{fb} represents the variability in mean freeboard and is assumed to be unbiased. If there is a nonzero mean freeboard when widespread snow-ice formation occurs, this will introduce an additional systematic bias as discussed in section 4.3.

[55] Defining F as the total freeboard the ice thickness determined from ICESat can be determined from (4) as

$$h_i = -(6.0 \pm 1.1)h_s + (9.1 \pm 0.8)F. \quad (6)$$

[56] The overall error is identical to (5) except that $\rho_s - \rho_w$ is substituted for ρ_s and the freeboard, fb, is replaced by the total freeboard, F. The precision of ICESat elevation measurements is about 2 cm [*Kwok et al.*, 2006]. Assuming this is a lower limit for the accuracy of total freeboard retrieval, then for a typical snow depth of 15 cm and using the same errors in densities as before, the error in ice thickness for each method is then given approximately by

$$\sigma_{hi(SSM/I)} \simeq \left[61 + 9.6\sigma_{hs}^2 + 83\sigma_{fb}^2 \right]^{\frac{1}{2}} cm \quad (7)$$

$$\sigma_{hi(ICESat)} \simeq \left[253 + 36\sigma_{hs}^2 + 332 \right]^{\frac{1}{2}} cm. \quad (8)$$

[57] Then, even with an accurate determination of h_s, the ice thickness determined from passive microwave is more accurate than ICESat provided the mean freeboard is less than approximately 3 cm, which is generally the case for level ice. Interestingly, any error in h_s has a greater effect on the ICESat estimate because this will be interpreted as a change in freeboard.

[58] If however, we assume zero freeboard, the ICESat error can be reduced substantially. In this case, F provides an estimate of h_s and the error is approximated by

$$\sigma_{hi(ICESat)} \simeq \left[99 + 36\sigma_{fb}^2 \right]^{\frac{1}{2}} cm, \quad (9)$$

which will almost always be lower than for the passive microwave-derived thickness and does not rely on an independent determination of snow depth, but is subject to the same possible bias.

[59] Ice thickness from radar altimetry will potentially be the most accurate for high freeboards, since it provides a direct measure of freeboard. Since we must use that same snow depth, the error in ice thickness is the same as that given by (7) for passive microwave. Whether any particular method is more accurate depends critically on whether the error in freeboard determination can be better constrained than the assumption of near-zero freeboard.

[60] Preliminary results from ICESat give winter mean ice thicknesses exceeding both the ASPeCt and passive microwave ice thicknesses by much more than the estimated error [*Zwally et al.*, 2008]. This is in part explained by differences in what is being measured. Altimetric measurements include both level ice and ridges, and thus represent the true mean ice thickness, while the SSM/I ice thickness is a better estimate of level ice thickness. *Tin et al.* [2003] and *Allison and Worby* [1994] show that ridging can cause the mean thickness to more than double relative to the level ice thickness. *Worby et al.* [1996] show, however, that these estimates do not necessarily match thicknesses from drill hole data, which may in part be due to sampling bias. We are then left with the question of how to interpret the derived ice thickness. While the overall mean ice thickness may be a more meaningful quantity than level ice thickness, there are some instances where the latter may be more useful. First, level ice thickness more closely reflects the influence of thermodynamic growth. As such, changes in level ice thickness provide a different measure of the pack ice cover's response to environmental forcing. Second, the bulk of the heat exchange between the atmosphere and the ocean occurs through level ice (and leads), and level ice dominates the salt flux to the ocean. Nevertheless, given the importance of deformation to the development of Antarctic sea ice, it will be difficult to meaningfully assess the impact of interannual or regional variations in ice thickness without a way to assess the role of deformation, either through modeling or comparison with altimetric determinations of ice thickness.

[61] Although no sampling bias was evident in comparison of regional means with those coincident with in situ data, there remains the possibility of bias due to lack of observations in areas that were inaccessible. This would mostly occur in areas of thick ice and snow. For example, in the Amundsen and Bellingshausen seas, there are no in situ data near the coast in the region of deep snow. While high freeboards in these regions would limit the usefulness of the technique described here, we note that these areas tend to have deep snow and heavy snowfall, so we surmise that freeboards are no more likely to be positive than elsewhere.

5. Discussion and Conclusions

[62] Using monthly mean snowfall over sea ice from ERA-40 with passive microwave satellite retrievals of snow depth, ice concentration, and ice velocity, we have derived maps of monthly mean Antarctic snow-ice thickness for level ice for April–October, 1979–2001. Snow ice is predicted to occur for all regions throughout the growth season, with a mean thickness in September of 16 cm. The least snow ice is found in the Weddell Sea, while the highest is found along the coast in the Pacific sector of the East Antarctic and in the Amundsen Sea. Thick snow ice is also found in the outer Ross Sea. Predictably, snow-ice thickness is most dependent on snow accumulation. Somewhat surprising, however, is that there is little relationship with snow depth, but a strong dependence on ice divergence and new-ice formation. Physical arguments can be made for each of these phenomena. In the first case, this implies that once

snow-ice formation begins, there is little increase in snow depth with increasing accumulation. This could be true if the ocean heat flux is high enough to melt ice from below and maintain near constant ice thickness. This has some support from modeling studies [*Maksym and Jeffries*, 2000] and field observations [*Lytle and Ackley*, 2001], and possibly the observed drop in mean snow depth toward the end of winter. However, the strong relationship between snow depth and ice thickness observed in drilling data [*Worby et al.*, 1996; *Jeffries et al.*, 1998b] and between snow depth and snow-ice thickness [*Jeffries et al.*, 2001] argue against this. In the second case, the model will predict reduced snow ice for increased new-ice formation because this reduces the mean snow depth, and hence increases the apparent increase in mean snow depth month-to-month. This implies that new, snow-free ice is less likely to flood than older snow-covered ice, which is plausible.

[63] Despite the lack of relationship between precipitation and snow depth, there are some regional trends. There are significant positive trends in snow depth and accumulation (defined as the seasonal total of precipitation that falls on ice) in the Ross Sea, while there are coincident negative trends in the Bellingshausen. This coincides with a strong downward trend in snow-ice production in the Bellingshausen Sea. In the Ross Sea, a coincident trend in new-ice production counteracts any effect of increased snow depth. These effects do not appear to be due to trends in precipitation, but rather to the length of the ice season, as they coincide with an increase in ice extent in the Ross Sea and a decrease in the Bellingshausen.

[64] We must admit the possibility that these effects are artifacts. It seems reasonable to expect that an increase in precipitation should be reflected, at least in some regions, by a corresponding increase in snow depth. Likewise, we might expect an increase in ice and snow divergence to be reflected in a relative drop in snow depth (given a similar snowfall rate). Given that mean monthly increases in satellite snow depth are significantly less than snowfall rates, it is possible that errors in snow depth retrievals are sufficiently large to obscure any real observable variability due to precipitation and ice dynamics. Clearly, improvements in satellite snow depths and validation for a variety of snow conditions are needed to properly evaluate the role of snowfall variability in the mass balance of sea ice.

[65] Modeled snow-ice thicknesses compare well with analysis of ice cores from nine fall and winter cruises for all regions except the East Antarctic, where too much snow ice is produced. There is some uncertainty in these estimates, as they vary significantly depending on the magnitude of several poorly constrained processes. For example, snow losses due to drifting into leads of 2 cm per month reduces the mean snow-ice thickness by about 3 cm. Use of monthly-mean ice drift most likely underestimates new-ice production due to daily- and sub-daily-scale ice deformation, which also leads to an overestimate of snow-ice production. Perhaps the most important unknown is just how much snow is incorporated into the snow ice upon flooding and refreezing. We have assumed that the snow settles upon wetting so that the slush is initially equal parts seawater and ice. Without this settling, estimates of snow-ice thickness increase by about 40%, producing snow-ice thicknesses at the upper bound of the range of observed values (though this actually provides the best agreement with what most authors define as snow ice). Measurements of snow-ice layers in ice cores, as defined by negative δ^{18}O values suggest that the snow fraction is closer to 12% [*Jeffries et al.*, 2001]. This implies that either a substantial fraction of this ice is not snow ice, or exchange of brine during freezing reduces the meteoric ice content of the snow ice [*Lytle and Ackley*, 2001; *Maksym and Jeffries*, 2001]. While this might increase the meteoric component of granular ice layers of frazil origin that lie beneath the snow ice, thus conserving the overall meteoric fraction, some of this ^{16}O enriched brine might drain into the sea [*Maksym and Jeffries*, 2001]. The total meteoric-ice thickness (meteoric ice plus infiltrated seawater) provides a lower limit for the snow-ice fraction that is roughly one third of the upper limit. On the basis of modeling of this process, *Maksym* [2001] suggested that the true value is roughly half way between the two limits. If this is true, this study slightly overestimates the amount of snow ice, but this can be readily explained by a small increase in ice deformation, snow drift or sublimation. A better understanding of the small-scale physical processes that govern the evolution of a freezing slush layer would clearly aid in the interpretation of both models and in situ data.

[66] Given the range of possible influences on snow depth and snow-ice evolution and their respective uncertainties, it is difficult to asses the accuracy of the ERA-40 snowfall in this study. The best we can say is that for most areas, snowfall from ERA-40 are not inconsistent with observations. There are, however, several key areas where this may not be true. Figure 13 shows the amount of snow ice as a percentage of the total derived ice thickness (using the best estimate thickness with an assumed 1 cm mean freeboard). In most regions, the snow-ice contribution compares quite well with in situ observations. This suggests that in general, both satellite snow depth and ERA-40 snowfall are reasonably accurate. As previously noted, there are areas where the contribution of snow ice to the total thickness of the ice is too high. This is true for much of the East Antarctic, particularly near Mawson and along the coast between Davis and Dumont D'urville, where the contribution exceeds 100%. This ratio also exceeds 100% along the coast of Marie Byrd Land in the Amundsen Sea, suggesting the ERA-40 snowfall is too high in each of these regions. Note however, that almost no in situ data is available along the Amundsen Sea or much of the East Antarctic coast in winter (indicated by cruise tracks shown in Figure 13).

[67] While no long-term accumulation data are available over sea ice, extensive compilations do exist on the continent [*Vaughan et al.*, 1999]. These have recently been interpolated over the entire continent using passive microwave satellite data [*Arthern et al.*, 2006]. A comparison of this data set with mean annual accumulation on the continent from ERA-40 shows that ERA-40 tends to overestimate snowfall principally near the coast adjacent to the regions noted above (Figure 14), although other authors come to somewhat different conclusions based largely on regional model results [*van den Broeke et al.*, 2006; *Monaghan et al.*, 2006a]. An alternative hypothesis is the underestimate of ice drift speed from passive microwave in the East Antarctic [*Heil et al.*, 2001b] reduces modeled ice

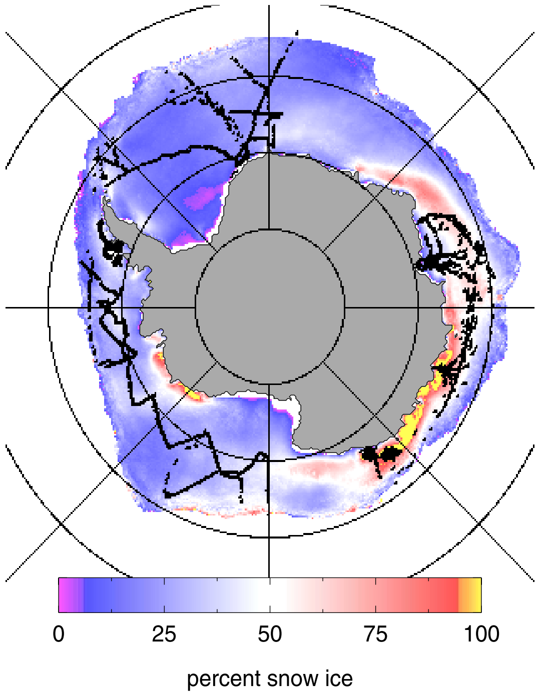

Figure 13. Average modeled snow-ice thickness as a percentage of total ice thickness for September. Cruise tracks for August–October from ASPeCt data set are overlaid in black. The contribution of snow ice to the total ice thickness agrees fairly well with ice core data except for East Antarctica, where too much snow ice is produced. Note that there are almost no observations where the snow-ice percentage approaches 100%.

export and new-ice production along the coast, thereby causing an overestimate of snow-ice production. A more focused study that accurately monitors sea ice drift and new-ice production in conjunction with snow depth evolution is necessary to resolve these issues.

[68] By using snow-ice formation as a proxy for zero-mean freeboard, we calculate the level ice thickness from the satellite snow depth. The mean level ice thickness for each region shows quite good agreement with coincident shipboard observations of both level ice thickness and snow depth for August–October. The mean modeled ice thickness for all of Antarctica was 42 cm, while the observed value is 51 cm. Nonzero mean freeboards appear to be the largest potential source of error. Assuming a positive mean freeboard of 1 cm (equivalent to a 3 cm negative bias in satellite snow depths), the mean thickness improves to 53 cm. For this case, the largest errors are in the Ross and Amundsen/Bellingshausen sectors, where negative mean freeboards lead to somewhat high ice thicknesses. We see no evidence for bias in level ice thickness due to sparse sampling, except for the Ross Sea where thinner ice close to the coast is undersampled by ships, in contrast to the conclusions of *Timmermann et al.* [2004].

[69] While these results are encouraging, because of the substantial variability in mean freeboard in drilling data (0–3 cm in the Amundsen Sea [*Adolphs*, 1998], 1–5 cm in the Weddell [*Eicken et al.*, 1994]) evaluating the interannual variability in ice thickness from passive microwave snow depth retrievals will remain problematic. Each centimeter of freeboard creates a bias in ice thickness of about 10 cm. We estimate the combined error due to all sources to be 10–20 cm for late winter. This is larger than observed regional and interannual ice thickness variability, so without improvements, the method will be of limited utility. We note, however, that many of the same errors apply to altimetric methods. In fact, for small freeboards (<3 cm), the method presented here may be more accurate than ICESat. In these cases, ICESat could instead provide an accurate direct measure of snow depth. We must stress, however, that each method measures potentially quite different things: Altimeters give the average thickness of all ice whereas the method presented here provides an estimate of the level ice thickness only.

[70] There are a number of avenues for improvement of ice thickness determination. First, the accuracy of the satellite snow depths needs to be evaluated under a variety of conditions. The snowpack undergoes a variety of processes such as depth hoar formation, melt/freeze cycles, and formation of icy layers [*Massom et al.*, 2001], all of which impact its microwave scattering properties and density. Use of a prognostic model of snowpack evolution may help constrain both observed variability in passive microwave signatures and snow densities used to estimate ice thickness. Second, obtaining an independent estimate of mean freeboard is needed. Drilling data and ice core evidence suggest that higher snow-ice production rates are associated with lower mean freeboards. Development of a statistical rela-

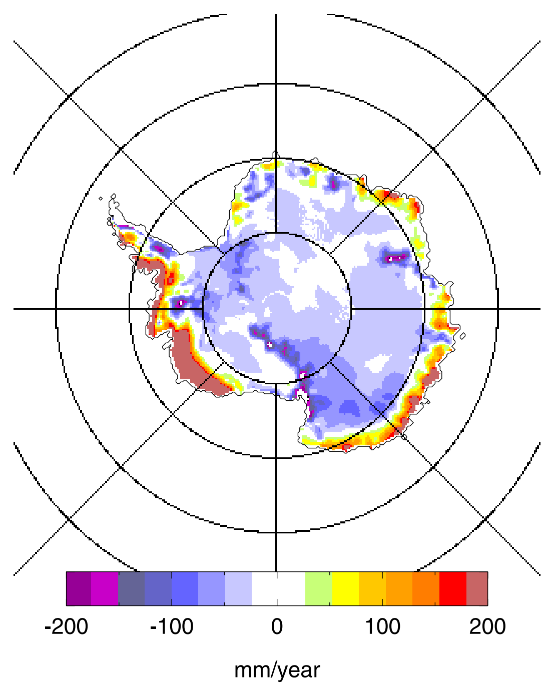

Figure 14. Difference between ECMWF ERA-40 annual accumulation and that of *Arthern et al.* [2006]. Significant differences along the coastal areas, particularly for the Amundsen and East Antarctic sectors, suggest that the ERA-40 data may overestimate snowfall over sea ice in these areas.

tionship between snow-ice production rates and mean freeboard, possibly in conjunction with a prognostic sea ice model, would allow us to adopt a stricter criterion to identify where freeboard is likely to be zero. Combining these methods with both laser and radar altimetry is likely to produce the most accurate estimates of sea ice thickness.

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